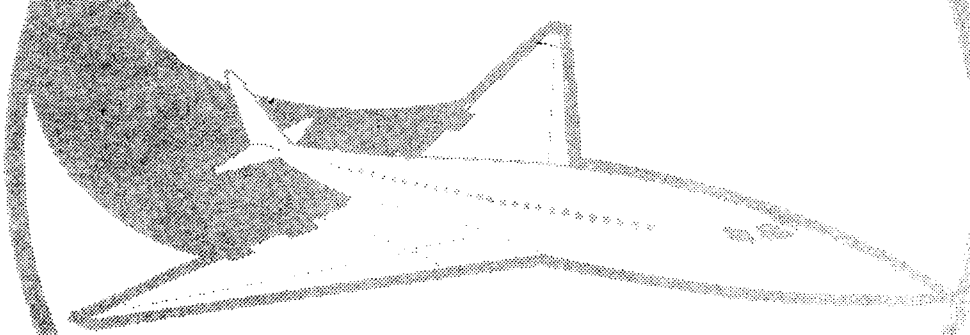
technical note

Soft-Ground Arresting System for Commercial Aircraft

Interim Report



February 1993

DOT/FAA/CT-TN93/4

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NOTICE

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT/FAA/CT-TN93/4		

4. Title and Subtitle	5. Report Date
SOFT-GROUND ARRESTING SYSTEM FOR COMMERCIAL AIRCRAFT	February 1993
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Robert Cook	DOT/FAA/CT-TN93/4
9. Performing Organization Name and Address	10. Work Unit No. (TRAIS)
MiTech Incorporated Pleasantville, NJ 08232	11. Contract or Grant No.
	13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Aviation Administration Technical Center Atlantic City International Airport, NJ 08405	Interim Report
	14. Sponsoring Agency Code ACD-110

15. Supplementary Notes

This project was monitored by the following FAA personnel.
Rick Marinelli, Hector Daiutolo, and Larry VanHoy

16. Abstract

A soft-ground arresting system provides an economical and nondestructive means for decelerating an aircraft that would otherwise be unable to stop safely within the confines of the runway including the safety or overrun area. This report validates a mathematical model developed to predict deceleration of an aircraft as it travels through a soft-ground arresting system. Full-scale tests were conducted at the Federal Aviation Administration Technical Center using the FAA's instrumented B-727 aircraft. The speed of the aircraft entering the beds ranged from 20 to 80 knots. The dimensions of the bed were as follows: foam thickness range was from 6 to 18 inches; test bed length was from 88 to 176 feet; width was always 40 feet. In each test the deceleration experienced by the aircraft was recorded in addition to its velocity, landing gear loads, and brake torque. The results of these tests showed that actual measured parameters from the aircraft were within 10 percent of the values predicted by the mathematical model; thus validating the accuracy of this model. The 18-inch-thick foam bed provided the most effective deceleration without exceeding the stresses encountered by the aircraft during normal operation. Fire and rescue equipment can maneuver and conduct emergency operations within the foam arrestor bed without difficulty.

17. Key Words	18. Distribution Statement
Soft-Ground Arresting System Overrun, Deceleration Phenolic Foam, Runway Safety Area Foam Bed	Document is on file at the Technical Center Library, Atlantic City International Airport, New Jersey 08405

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	36	

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1. INTRODUCTION.

This report describes the theoretical development and verification testing of a soft-ground arresting system for commercial aircraft. The system is intended to provide an economical and nondestructive means for decelerating large aircraft that would otherwise be unable to stop safely within the confines of the weight-bearing surface of a runway overrun or safety area.

1.1 AIRCRAFT OVERRUN CONSIDERATIONS.

Airports are designed with runway dimensions that provide sufficient length for acceleration to takeoff speed or deceleration to a complete stop, within the confines of the runway. It is possible, however, that an aircraft may not be able to be stopped before running off the runway in the event of unusual circumstances. These could include occurrences such as aborted takeoff, brake failure, or runways covered with snow, slush or ice.

To reduce the probability of accidents under such conditions, most commercial airports have established a runway safety area, an additional weight-bearing surface extending to a maximum of 1000 feet beyond the end of the runway (figure 1). FAA Advisory Circular (AC) 150/5300-13, Airport Design, provides a full description of the standards. If the safety area does not provide sufficient distance to allow a safe stop, the aircraft will roll past the end of the usable surface with potentially disastrous results. The hazards are even more serious at airports where runways terminate in close proximity to busy roads, rail lines, abruptly falling terrain, or bodies of water.

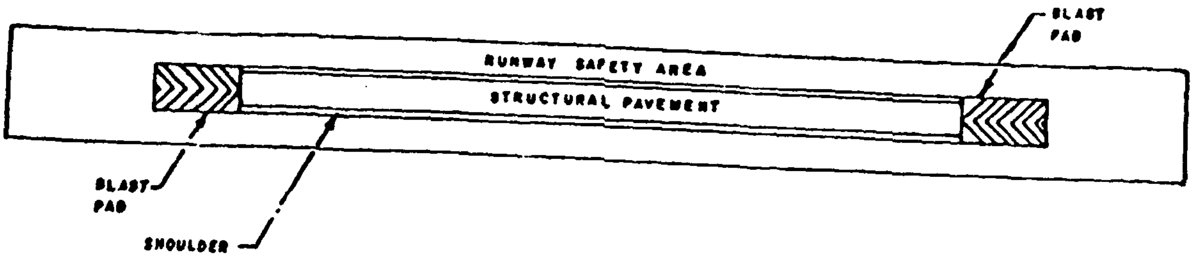


FIGURE 1. STANDARD RUNWAY SAFETY AREA (AC 150/5300-13)

A limited number of methods are currently available for preventing such overruns. These include active systems, such as arresting cables and nets, and passive systems, such as soft-ground "arresting" barriers.

The active systems are commonly used on aircraft carriers and at military airfields. They utilize cables and nets stretched laterally across the landing surface and attached to a high-energy dissipation device. In the event of a potential overrun, the tail hook provided on the aircraft is lowered to engage the cable, allowing the aircraft to be brought to a

safe stop over a short distance. These systems are extremely effective, but entail considerable penalties by requiring costly aircraft enhancement to fit the necessary hook device and provide the structural airframe strengthening required. They are not economically practical for use on commercial civilian aircraft.

The soft-ground arrestor barrier is a passive arresting system, employing soft materials to absorb the kinetic energy of the "runaway" aircraft, and can be installed in the safety area of the runway. The retarding force for decelerating and stopping the aircraft is derived from the drag on the aircraft wheels as they travel through the material. Effectiveness of one such soft-ground arresting system was evaluated at the British Royal Aircraft Establishment using the urea formaldehyde foamed plastic (reference 1). Other materials that exhibit energy absorbing properties are described below, along with physical dimensions of full-scale arrestor systems that might be used in an operational environment:

- Gravel bed - a bed consisting of 1/4 inch to 3/8 inch gravel. The bed is uniformly tapered from 0 to approximately 4 feet over a distance of approximately 400 feet. This results in a 1 percent grade.

- Soft soil - a bed of soft soil (e.g., sand and clay) at the end of the runway. One of the drawbacks of this type of an arrestor system is that sand and clay are subject to strength changes due to weather conditions.

- Water ponds - an excavated area that has a length of approximately 400 feet. The area would be filled with water with a tapered depth of from 0 to approximately 3 feet.

- Phenolic foam - a bed of phenolic foam constructed in the runway safety area. The foam is available in 48- by 96- by 3-inch sheets and provides excellent energy absorption. It would be assembled into a bed that would taper from 0 to approximately 2 feet in a distance of approximately 400 feet.

- Foamcrete - a bed of aerated cement constructed in the runway safety area. It would be assembled into a bed that would taper form 0 to approximately 2 feet in a distance of approximately 400 feet.

Table 1 provides the advantages and disadvantages for each arrestment method. Based on this assessment, the FAA decided to evaluate phenolic foam in the first United States test of a soft-ground arrestor. The phenolic foam material was particularly attractive since it is environmentally safe, is a good energy absorber, and can be obtained with controllable density and thickness.

TABLE 1. COMPARISON OF VARIOUS AIRCRAFT METHODS

Arresting Method	Advantages	Disadvantages
Cables	Working systems are available	Requires aircraft modifications
Gravel	Inexpensive	Good in warm weather use only, and gravel spray can damage aircraft
Soft Soil, Clay and Sand	Inexpensive	Difficult to control physical properties in various weather conditions
Water Ponds	The system is re-usable at no additional cost	Good in warm weather use only and difficult to prepare
Phenolic Foam	Ease of construction, Stable physical properties and good crushing properties	The system requires repair after each use.
Foamcrete	Ease of construction	Corrosive properties may damage aircraft

1.2 BACKGROUND.

There were 33 runway overruns involving air carrier aircraft in the United States during the time period from 1978 to 1987. Review of International Civil Aviation Organization (ICAO) and National Transpsortation Safety Board (NTSB) accident reports (1975-1987) have provided some relevant information, but unfortunately, only a few of the incidents had complete data.

Information on the final resting locations of aircraft after an overrun is important because it indicates the amount of space used to dissipate the aircraft speed after leaving the runway. This information is depicted in figure 2 (reference 2). It is noted that a majority of the overruns stop within a lateral distance of 100 feet of the runway centerline and 1,000 feet longitudinally from the runway end. In this analysis, aircraft which veered off the runway prior to reaching the departure end were counted as overruns if they came to rest beyond the end of the runway.

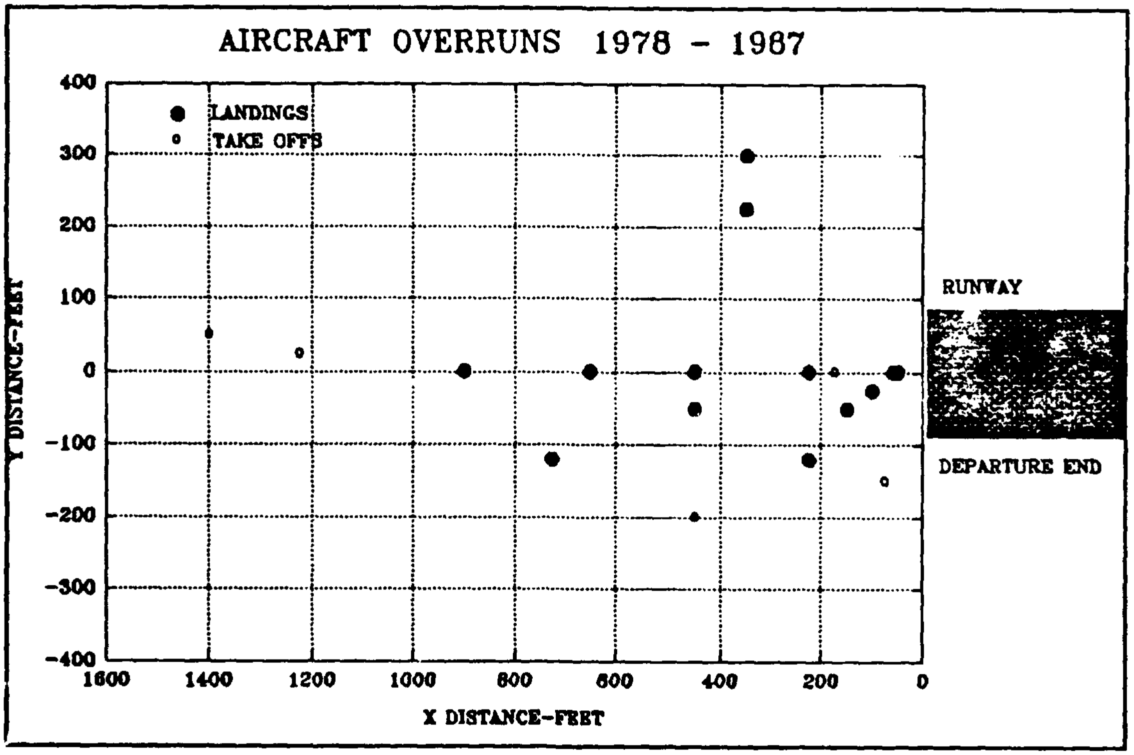


FIGURE 2. OVERRUN LOCATIONS

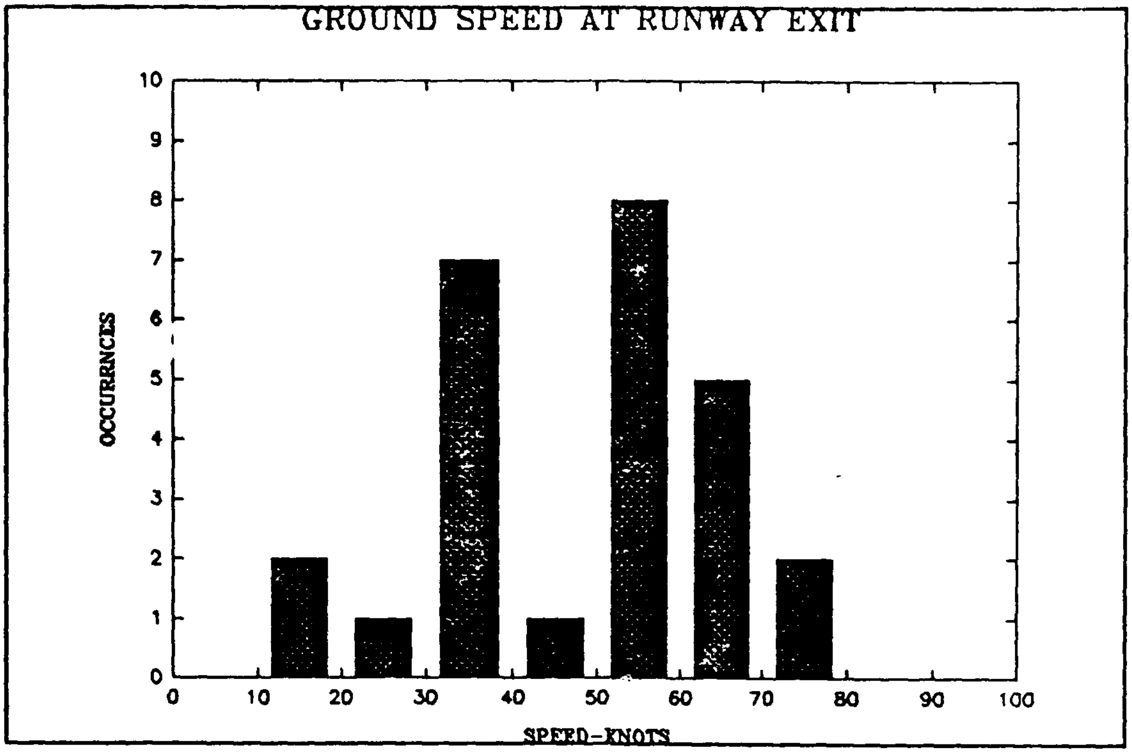


FIGURE 3. RUNWAY EXIT SPEEDS FOR *OVERRUNNING* AIRCRAFT

Figure 3 (reference 3), indicates that the speed of the aircraft, when exiting the end of the usable runway, can be as high as 80 knots. The majority of overrun events, however, occur at much lower velocities.

The statistics of these overrun accidents indicated that:

- Brakes may or may not be applied or available during the overrun.
- Reverse thrust may or may not be applied during the overrun.
- Runway surfaces may be dry, wet, or contaminated.
- The runway safety area may not be paved.
- There may be water or other hazards in the safety area.
- 88 percent of the overrun aircraft came to rest within 1000 feet of the end on the runway.

1.2.1 British R.A.E. Test Program.

The British test program used urea formaldehyde, a rigid foam material that is not available in the United States. The foam has very good energy absorbing capabilities and is quite stable in terms of physical properties, making it most suitable for use as an arrestor. The foam arrestor system is expected to provide consistent properties in all weather, and remain at the end of the runway for long periods of time with little or no attention for maintenance.

The foam test program results, reported by the British, indicated that the foam arrestor will provide a nearly constant deceleration of aircraft for a given thickness and specified compressive strength, regardless of aircraft braking effectiveness or local environmental conditions (reference 1).

1.3 FAA SOFT-GROUND ARRESTING SYSTEM PROGRAM.

The FAA, recognizing the potential safety benefits of such passive arrester systems but having had no previous experience within this area, decided to conduct various "real-world" tests involving actual aircraft engagement with prototype arrester installations. Although the exact foam material employed in the British tests is not available in the United States, other similar foam materials were identified which are likely to satisfy the design goals. Appropriate laboratory tests were conducted on these materials (such as crush strength, toxicity, and freeze-thaw reference 3) to define their characteristics.

The FAA test program involved development of an analytical model to provide essential preliminary identification of promising arrester installation design parameters, followed by limited full-scale testing of several prototype foam test beds using an instrumented FAA Boeing 727 aircraft.

The test beds were configured to provide for gradual buildup of arrestor material thickness and aircraft speeds before reaching the foam depths required for an actual arrestment. This was necessary to insure that no damage would be sustained by the test aircraft. Eight different arrestor tests were performed which included speeds to 80 knots and test beds which were 6, 12, and 18 inches thick.

1.3.1 Development of Analytical Model.

An analytical model is a computer program intended to simulate the action and reaction of known elements. The characteristics of the foam arrester material to be used can be introduced into the formulas. Having also determined and entered the specific aircraft parameters (weight, speed, configuration, etc.), a prediction of deceleration rate and imposed mechanical loads for the aircraft can then be obtained. Once the validity of the analytical model has been verified by full-scale testing, the relative effectiveness of other arresting materials can be reliably predicted. Further, by substituting the specific parameters of other types of aircraft, the model can be used to predict arrester effectiveness for a wide range of user aircraft. The ultimate usefulness of the correctly developed and properly validated analytical model will be realized in the relative ease with which passive arrester barriers can be designed for specific airport runways.

The model developed and validated during this effort employed finite element analysis techniques to model the interface between the aircraft wheels and the phenolic foam. The three dimensional analytical model (reference 4) simulates the aircraft landing gear nonlinear struts and tires and the flexible upper body structure. This allows the model to predict the dynamic response of the aircraft to the additional runway surface roughness introduced by the crushed foam. In addition the model assists in prediction of the wheel vertical and

drag loads introduced by passage through the foam. The analytical model runs on a 386 based personal computer using the Fortran programming language. It was designed to handle various aircraft speeds, weights, test bed configurations, and several other parameters.

The computer simulation of the test aircraft was a key element in determining how the test program would be conducted. Validation of this computer model was required in order to verify the claims made in previous analytical studies (references 3, 5) regarding the performance of the foam arrestor.

Figure 4 shows the features of the wheel/foam interface model. The tire is divided into arc segments, α, as shown, and the foam pressure existing at that level in the foam is multiplied with the arc segment area (arc length times tire width) to determine the force. This force is then resolved into vertical and drag components. The components are then summed to obtain the total vertical force and drag on the wheel due to the foam. The wheel is also divided into radial element springs (reference 6) which determine the vertical loads and drag resulting from the bump introduced by the compacted foam. The forces from both the foam and bump are summed to obtain the total axle vertical load and drag. Wheel axle vertical motion is allowed in the model which provides the coupling to the aircraft wheel struts and therefore to the rest of the aircraft.

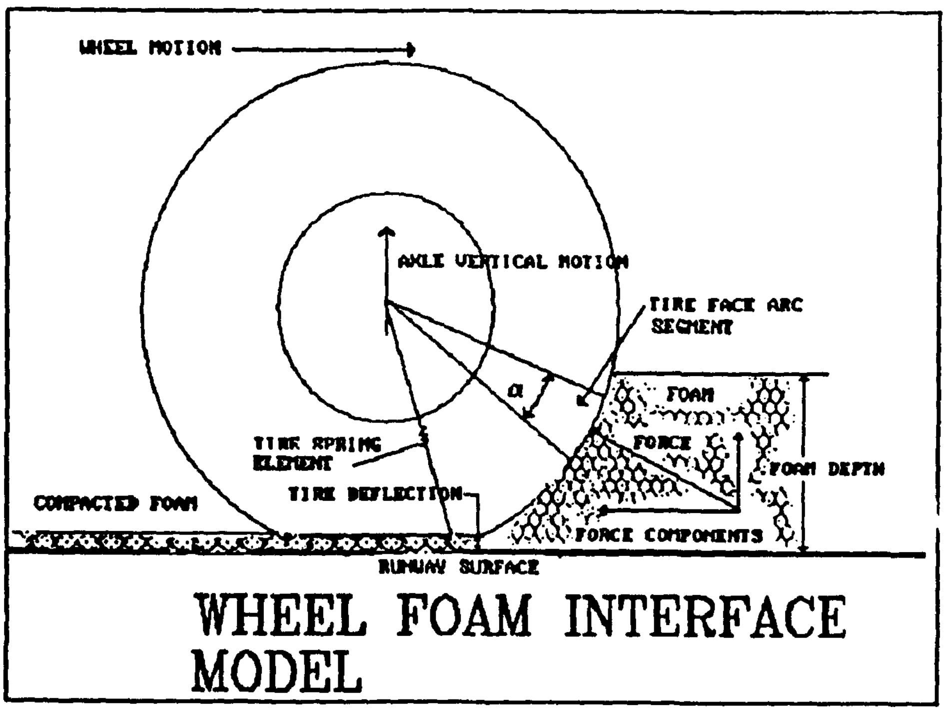


FIGURE 4. MODEL FOR DETERMINING WHEEL LOADS

1.3.2 Case Studies.

Analytical studies (references 3, 5) were used, along with the statistics of overruns, to simulate aircraft (references 4, 6) engagements with the foam arrestor. Two case studies were modeled, with results depicted in figure 5. The analytical model was used in both of the following cases:

Case 1 (Landing) - Modeling was accomplished on an actual 1984 SAS DC-10 overrun accident at JFK International Airport (reference 3). This accident resulted in major damage to the aircraft. The aircraft went off the end of the extended runway and stopped in Thurston Bay. Figure 5 was extracted from this study and shows the modeled estimated performance of a foam arrestor designed for use on this runway at JFK International Airport. The "Without Arrestor" indicates that the aircraft traveled a considerable distance beyond the end of the runway as actually happened. The "With Arrestor" shows that the aircraft motion would have been arrested prior to entering Thurston Bay.

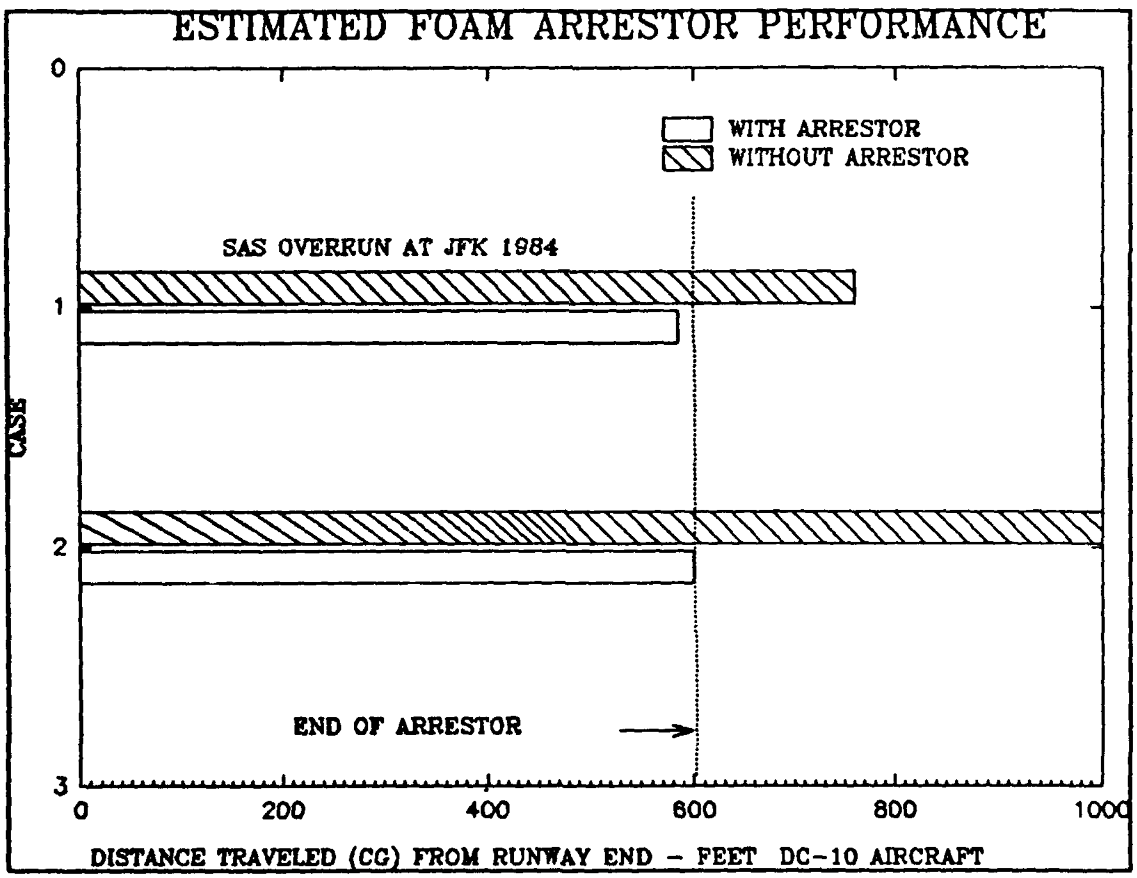


FIGURE 5. ESTIMATED FOAM ARRESTOR PEFORMANCE AT JFK INTERNATIONAL AIRPORT

Case 2 (Takeoff) - This case, also depicted in figure 5, represents a simulation of a hypothetical DC-10 aircraft aborted takeoff. The takeoff is simulated on an icy runway where the coefficient of friction is very low. As indicated, the aircraft will stop before the end of the safety overrun area when a foam arrestor is in place. Without the arrestor the aircraft will travel past the paved surface to a point well beyond the 1000 feet of clear area before stopping. If the clear area beyond the departure end of the runway is not paved then the event outcome becomes unpredictable since the bearing strength properties of soil vary widely with environmental conditions.

1.3.3 Transition to Full-Scale Validation Testing.

Preliminary analysis indicated that a soft-ground arresting system would be of benefit in preventing aircraft mishaps from overruns of runway ends at certain locations. In addition, the computer modeling efforts appeared promising in their ability to provide predictable results.

Since there was an established need to evaluate a soft ground arresting system and an analytical model was available for predicting the results of a soft-ground arresting event, the next step was to verify the model using a live test. Phenolic foam was previously identified as the first choice for the soft-ground arrestor test. The next step was to organize a plan to proceed with follow-on testing using this material.

2. FULL-SCALE VALIDATION TEST EFFORT.

This chapter provides details of the soft-ground arrestor tests using phenolic foam conducted at the Atlantic City International Airport, NJ, from March 1991 through June 1991. The actual tests were photographed as they occurred. Figure 6 shows the test aircraft, an FAA Boeing 727, within the test bed. Figure 7 depicts the rutting which resulted from the test aircraft passing through the test bed.

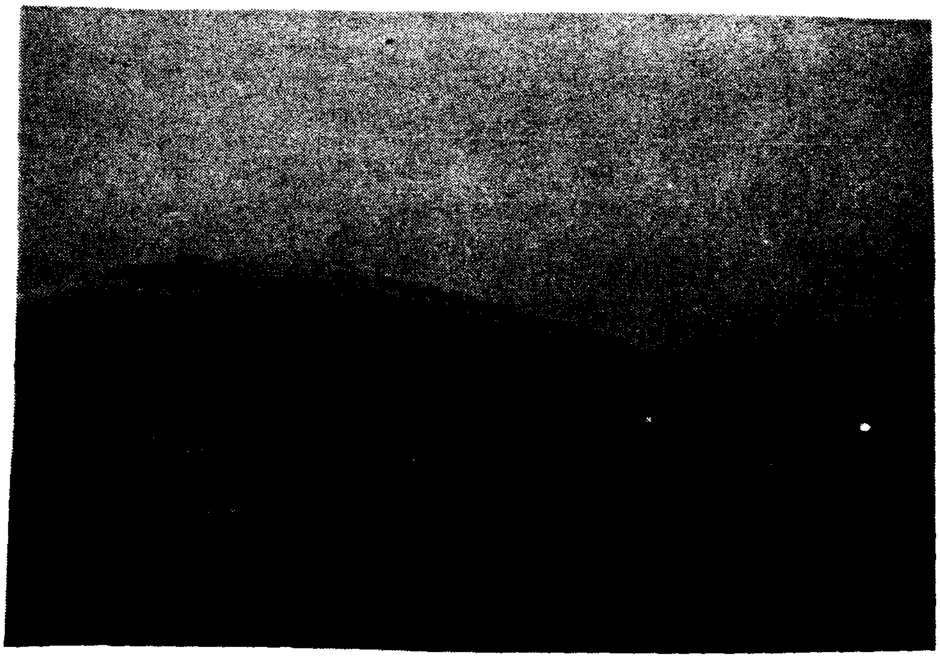


FIGURE 6. FAA BOEING 727 TEST AIRCRAFT ON FOAM BED

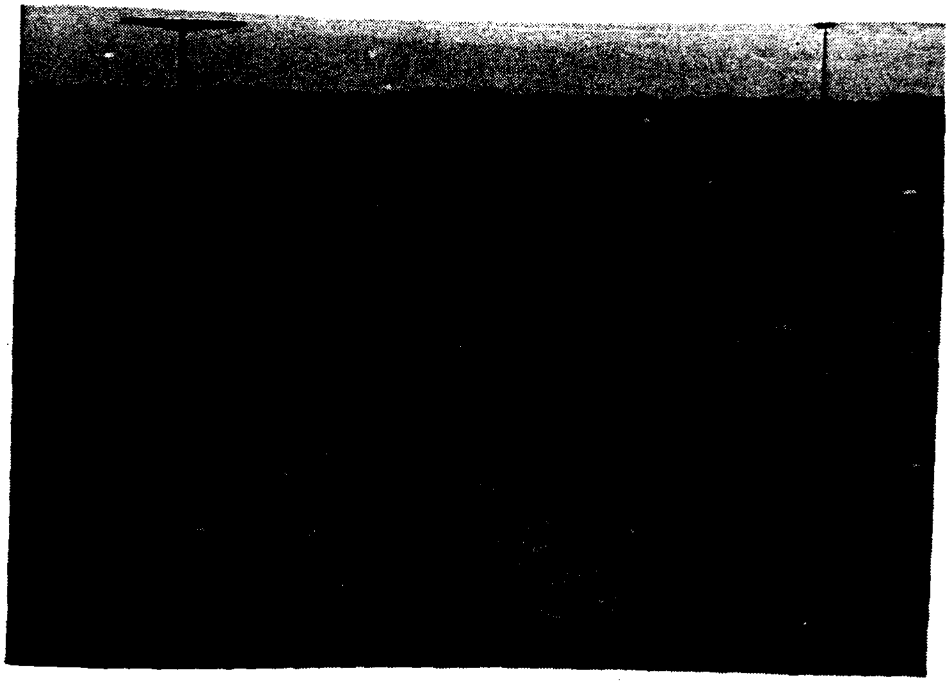


FIGURE 7. FOAM BED AFTER TEST AIRCRAFT PASSAGE

2.1 FAA TEST PROGRAM OBJECTIVES.

The specific objectives of the FAA aircraft arrestor test program were as follows:

- To validate the analytical method (model) for predicting effectiveness of soft-ground arresting systems and materials in decelerating aircraft to a safe stop under emergency conditions.

- To obtain specific information about the effectiveness of phenolic foam as a basic arrester system component.

- To determine whether fire/rescue personnel and equipment can maneuver and conduct emergency operations within the foam bed after an emergency arrest has occurred.

2.2 TEST DESIGN.

2.2.1 Location of Tests

The soft-ground tests required the use of a ramp and taxiway. Since facilities were available at the FAA Technical Center, the test beds were constructed at this location on the FAA ramp and Taxiway A. The selection of the site was dependant on the aircraft speed, braking and test bed size, with the ramp location used in preference to the taxiway site whenever possible.

Table 2 shows the location, test bed size, and other parameters of aircraft motion.

TABLE 2. SUMMARY OF TEST PARAMETERS

Test Name	Location	Entry Velocity (knots)	Test Bed Max. Depth (inches)	Test Bed Length (feet)
T1-S1-20K	FAA Ramp	20	6	88
T1-S2-40K	Taxiway A	40	6	88
T2-S2-60K	Taxiway A	62	6	104
T1-S1-BRK-40K	FAA Ramp	40	6	88*
T2-S2-80K	Taxiway A	80	6	104
T4-S2-30K	Taxiway A	33	12	148
T4-S2-50K	Taxiway A	50	12	148
T5-S2-50K	Taxiway A	49	18	176

*Brakes were applied while the aircraft was in the test bed.

2.2.2 Test Material and Properties.

In order to function effectively as a soft-ground arrestor, the material must compress under the aircraft wheels. Phenolic foam was selected as the material for this test program. The physical dimensions of the phenolic foam panel were 48 by 96 by 3 inches. The phenolic foam is a structural material that is commercially available in the building industry. Laboratory tests were performed to characterize the compressive strength of the phenolic foam panel with results shown in figure 6. The stress shown on the ordinate of the graph is the pressure developed on the aircraft tire surface. The abscissa of the graph gives the deformation of the foam as a percentage of the total sample depth. This information is required as an input to the analytical model in order to determine the test bed configurations and hence the aircraft landing gear loads while in the test bed.

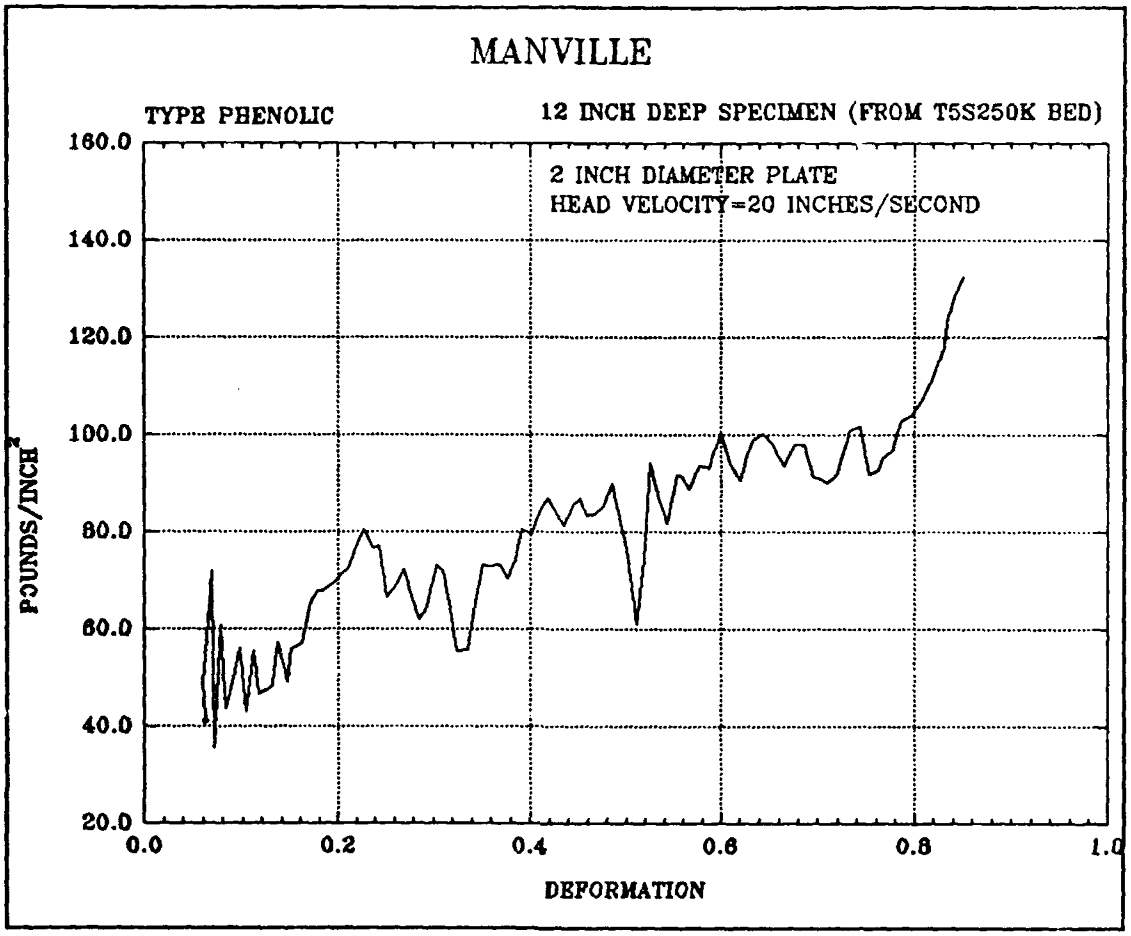


FIGURE 8. PHENOLIC FOAM COMPRESSIVE STRESS

2.2.3 Test Bed Size and Configuration.

The test program utilized eight test beds of various sizes and depths as depicted in table 2. All of the test beds were 40 feet wide. Five tests were conducted on 6-inch test beds, two tests were conducted on 12-inch test beds, and one test was conducted on an 18-inch test bed. The 6- and 12-inch test beds were selected to provide a gradual buildup of the test bed thickness. These were built up in 3-inch increments to provide a "ramp effect" to the entering test aircraft. The data from these tests were used to verify the analytical model and assure that no damage was sustained by the test aircraft. This provided the basis for the decision to proceed with larger test beds and higher aircraft velocities.

Figure 9 shows the cross-section of the test beds. There were four different types of phenolic foam test beds used in the testing. They were designated T1, T2, T4, and T5; T3 is missing because the test scheduled for that type bed was canceled. The test beds were formed by stacking and bonding 48- by 96- by 3-inch-thick foam panels as shown on figure 7.

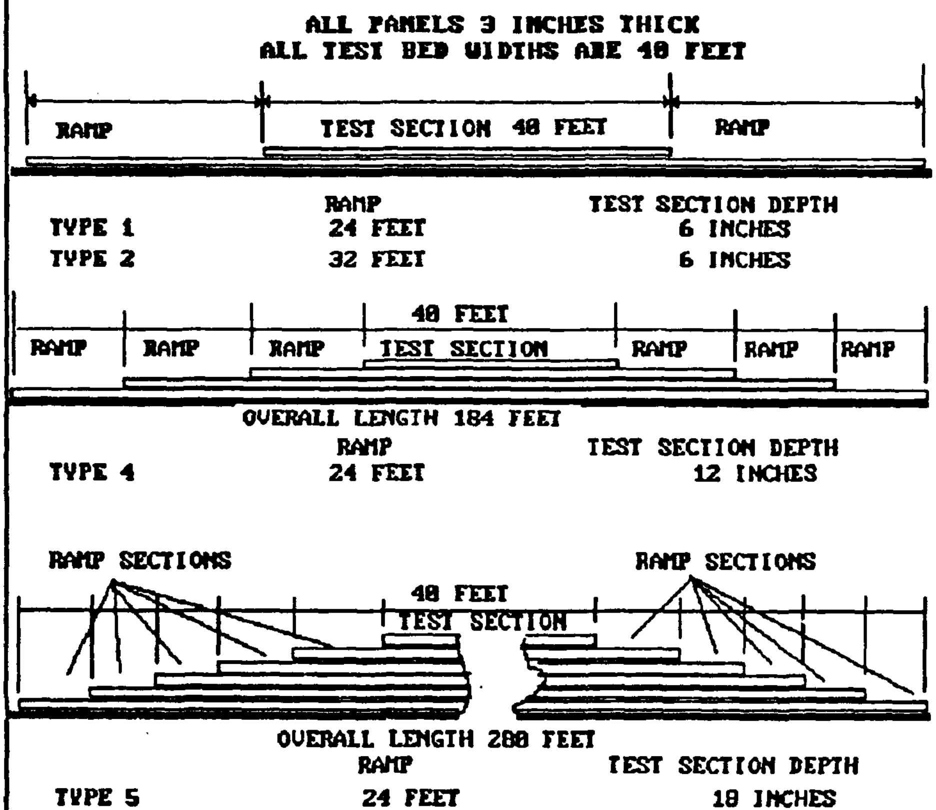


FIGURE 9. PHENOLIC FOAM BED CONSTRUCTION SKETCH (Not to Scale)

In order to expedite installation, the foam panel manufacturer bonded two panels together, at the factory, providing 6-inch-thick panels. These bonded panels were offset by 3 inches laterally and longitudinally to provide an overlap with adjoining panels. The panels were attached to the FAA ramp and Taxiway A surface with a latex based cement. Upon completion of construction of each test bed, it was covered by plastic sheeting for protection from the elements until testing was initiated.

2.2.4 Test Aircraft.

The FAA Boeing 727 was the aircraft used in the soft-ground arrestor test. It is powered by three engines, although for some tests the two outboard engines were covered and not used. This was a precautionary measure to prevent foam particles from entering the engines. The 727 was instrumented with a measurement system consisting of transducers, event synchronizers, signal processors, and a data collection system.

This use of an instrumented aircraft provided data needed to validate or modify the analytical model which predicts the performance of the Soft-Ground Arrestor System. Validation of the model allows it to be used in the design of a specific arrestor for a given application. This is useful in cases where many aircraft types (DC-9, DC-10, B-747, etc.) can be expected to make use of the arrestor system. Without the model, it would be necessary to test several aircraft types in a full-scale test to assure that the arrestor would perform as required.

2.2.5 Measured Parameters.

The measurement system on the FAA 727 provided the following:

- Determination of the landing gear loads in the vertical, longitudinal, and lateral directions

- Measurement of brake torque on the main gear

- Longitudinal, vertical, and lateral acceleration at the aircraft center of gravity

- Instantaneous ground speed from Inertial Navigation System (INS)

2.3 TEST PROCEDURES.

The procedures for conducting all of the tests were similar in nature. Several days before the scheduled test event, the test beds were installed on the FAA ramp and/or Taxiway A and a pretest meeting was held with all participants in attendance. The plan for the test was discussed and all participants had the opportunity to bring up questions about the plan or to make comments as desired. The test plan was a detailed step-by-step procedure which identified all tasks to be accomplished. Team leaders were designated to serve as photography leader, test site engineer, test engineer, instrumentation engineer, and aircraft commander. Each team leader was responsible for reporting to the aircraft commander when they were prepared for the aircraft run. Radio contact among team leaders was maintained throughout the test.

On the day of the test event, the test bed was uncovered and inspected to determine its readiness. The aircraft was then taxied to the predesignated starting point. After clearance was received from the airport control tower and all team leaders, the aircraft was accelerated to the test speed. In some cases all engines were used to accelerate the aircraft while in other cases only the number 2 (center) engine was used. Wing flaps were lowered to 15 degrees to reduce the possibility of foam being ingested into the engines. The flap position, however, had no influence on aircraft performance or test results.

The aircraft was steered along the centerline of the foam bed. Just prior to engaging the foam bed, aircraft power was reduced to idle so that the influence of thrust on the longitudinal acceleration would be minimized. The data collection system was activated at the beginning of the run and remained on while the aircraft was in the foam bed. Immediately upon exiting the foam bed, brakes were applied and the aircraft brought to a stop. The aircraft was then inspected for possible damage and all stray foam materials removed from recesses on the aircraft. The recorded data were reduced to engineering values on board the aircraft, and the landing gear loads were compared to limit values established for the test aircraft. A requirement for continuation of testing was that all landing gear loads had to remain below limit values for each test run.

Immediately after each test run the foam bed was inspected, photographs were taken, and the rut depths for each wheel track were measured and recorded. Where required, test passages of fire-fighting equipment, as described later, were accomplished.

After all photographic coverage, rut measurements, and other post-test tasks were completed, the foam bed was cleared from the test area and the site prepared for another test bed or final cleanup.

2.3.1 Test of Fire Equipment in the Foam Bed.

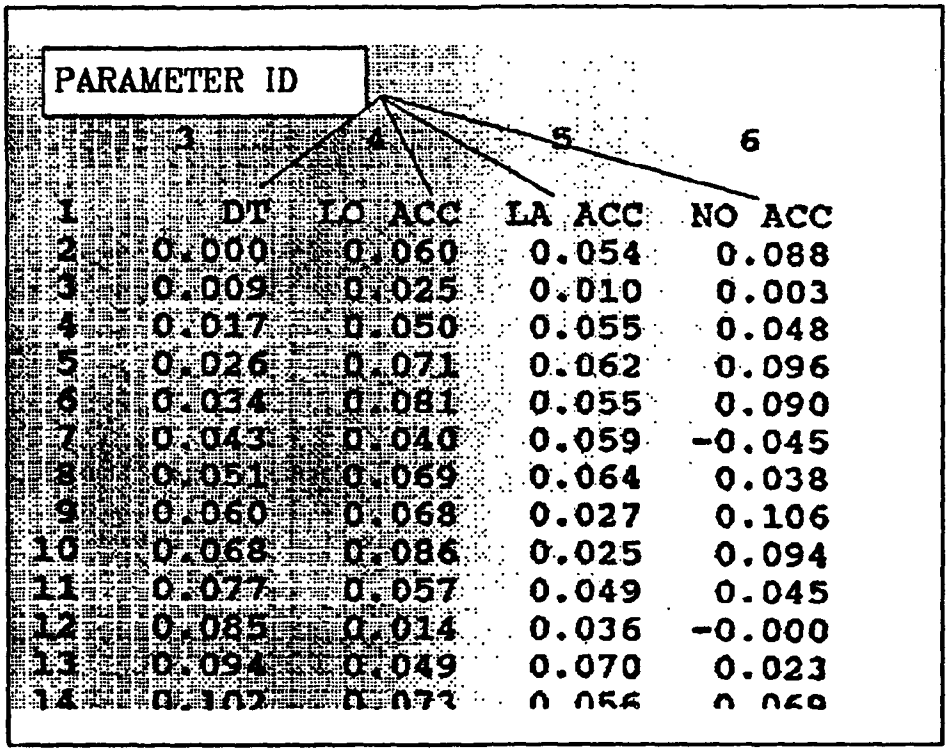
Subsequent to aircraft passage through the deepest test bed installation (18 inches), a P-19 fire truck was driven through the disturbed (rutted) foam bed to determine maneuverability of fire/rescue equipment within the immediate arrestment area. Figure 10 shows the fire truck on one of the foam beds.

FIGURE 10. P-19 FIRE TRUCK MOBILITY ON FOAM BED

2.4 DATA COLLECTION AND REDUCTION.

The time history data from the parameters being measured were digitized on the test aircraft and recorded on tape by the FAA onboard recording system. A software program was prepared by the FAA to reduce the recorded digitized data to engineering units after the test was concluded. This software program included the calibration data which converted the transducer electrical output voltages to the true parameter engineering values that are used in this report.

During the test event, the electrical output data from the transducers were digitized and recorded on a magnetic tape. The data on the tape were processed by a software program prepared by the FAA to provide the data in engineering values in tabular form along with time. Figure 11 on the following page is an example of a few columns of the data returned from the software program. Some editing was performed to insert column labels. The actual data output consisted of about 15 columns of data containing the accelerations shown in figure 11 plus the nose and main gear vertical, side and drag loads, ground speed, nose gear steering angle and several other data. Each column of data contains several hundred values depending on the length of the recording.



PARAMETER ID

	3	4	5	6
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3	0.009	0.025	0.010	0.003
4	0.017	0.050	0.055	0.048
5	0.026	0.071	0.062	0.096
6	0.034	0.081	0.055	0.090
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9	0.060	0.068	0.027	0.106
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11	0.077	0.057	0.049	0.045
12	0.085	0.014	0.036	-0.000
13	0.094	0.049	0.070	0.023
14	0.102	0.073	0.056	0.069

FIGURE 11. SAMPLE OF DATA FROM SOFTWARE

3. TEST RESULTS.

This chapter provides the test results from the soft-ground arrestor test program and discusses these results in relation to the accuracy of the analytical model for predicting deceleration and loads. A model thus validated can then provide a means for determining the effectiveness of foam materials as an aircraft overrun arrestor.

The data presented in this chapter resulted from Test 8, the T5-S2-50K Test (see table 2). Test 8 alone is discussed since it utilized the largest test bed of the 8 tests and represents the closest simulation of a full size test bed depth that would be required in actual airport operations. In addition, the foam bed depth for Test 8 was nearly the same as the depth used in the analytical studies. The 18-inch depth of the test bed, while ultimately chosen for reasons of economy, can be considered adequate to validate the foam arrestor concept. The complete and detailed test results for all test beds are provided in the appendix.

3.1 METHOD OF VALIDATING THE ANALYTICAL MODEL.

Since the objective of the test program was to validate the analytical model of an aircraft engaging a foam arrestor, the computer program used in the data analysis is the same as one used for the feasibility studies (references 3, 5) to predict the effectiveness of foam arrestor for stopping aircraft.

The usual procedure for validating analytical models involves performing actual measurements on the parameters pertinent to the output of the model. The measured and predicted results are then compared to determine the validity of the model. Note that because the measured results may contain errors, redundancy was employed in the measurement process to compensate for the errors. In this data analysis, measurements of decelerations and pertinent forces were recorded in order to provide the necessary compensation.

The performance of an actual arrestor is measured by its ability to decelerate the aircraft to a safe stop with minimal disruption to the vehicle and passengers. Arrestment of the aircraft is caused by opposing forces at the landing gear wheel/runway surface, reverse thrust and aerodynamic drag. The landing gear forces were measured in this test program. Statistical and graphical comparison of the measured forces with the forces predicted by the analytical model were used to verify the accuracy of the modeled predictions. With regard to aircraft power applied, only idle thrust was used during arrestments, and aerodynamic drag was found to be of virtually no consequence. As explained later, however, these factors were included in the analytical model computations.

3.2 TEST RESULTS - NO BRAKE APPLICATION.

Figure 12 shows a time history plot of the aircraft Center of Gravity (CG) longitudinal deceleration data obtained from Test 8. This plot also contains a time history plot of the longitudinal deceleration predicted by the analytical model of the aircraft engaging the foam bed. Clearly, the two results are similar. The "noisy" measured curve results from vibration of the landing gear in the drag direction, and this was not simulated in the computer model. The "noise" does not contribute to the aircraft deceleration because it is both positive and negative about a mean value, giving a net effect of zero. The otherwise similarity of the measured and predicted acceleration curves indicates that the computer model is an accurate representation of the aircraft engaging a foam bed, and that the wheel foam interface model correctly represents the drag on the landing gear. Longitudinal acceleration/deceleration is a measure of the drag imposed on the aircraft from foam bed retardation, engine thrust, and aerodynamic drag. For Test 8, the thrust of the engine was at idle setting, providing a force of approximately 1200 pounds. The aerodynamic drag at 50 knots was estimated to be about equal to the engine thrust at idle, but in the opposite direction, so that the net combined effect of thrust and aerodynamic drag was zero. Therefore the deceleration shown in figure 12 is a result of the foam bed drag on the landing gear wheels, and is a significant indicator of the retardation afforded by the foam arrestor bed.

The landing gear forces were measured so that these forces could be compared with the forces predicted by the analytical model. The nose gear and main landing gear components each provide a contribution to total deceleration. Figures 13 and 14 show a graphical comparison of the nose gear vertical forces and drag, measured during Test 8 and predicted by the model. The predicted and measured curves have been purposely offset in time about 1 second, with predicted values lagging, for ease of comparison. In figure 13, the measured vertical force is seen to be as much as 17,000 pounds above the initial static value of about 12,000 pounds. Similarly, the predicted result shows the same increase in the vertical load, as well as the same general dynamic characteristics. This increase in vertical load is a result of the upward force component due to the wheel/foam interaction, and consists of the bump resulting from the compacted foam and the moment induced by the main gear drag.

The loads on the landing gear must be accurately predicted, both in terms of static loads and dynamic loads, if the analytical model is to be useful in the design of a full-scale arrestor. Knowledge of the loads is also essential for test purposes to prevent damage to test aircraft. The results shown on figure 13 demonstrate that the model is quite accurate in predicting both static and dynamic landing gear vertical loads.

It is also important that the model accurately predicts the drag on the landing gear since this load determines the stopping distance of the aircraft in the foam arrestor. Figure 14 is a comparison of the measured and predicted nose gear drag. Figure 14 also depicts the longitudinal cross section of the foam bed as encountered by the nose gear during the computer simulation. The measured and predicted curves were again purposely offset by about 1 second, as described above, for ease of comparison. The "noise" on the measured drag

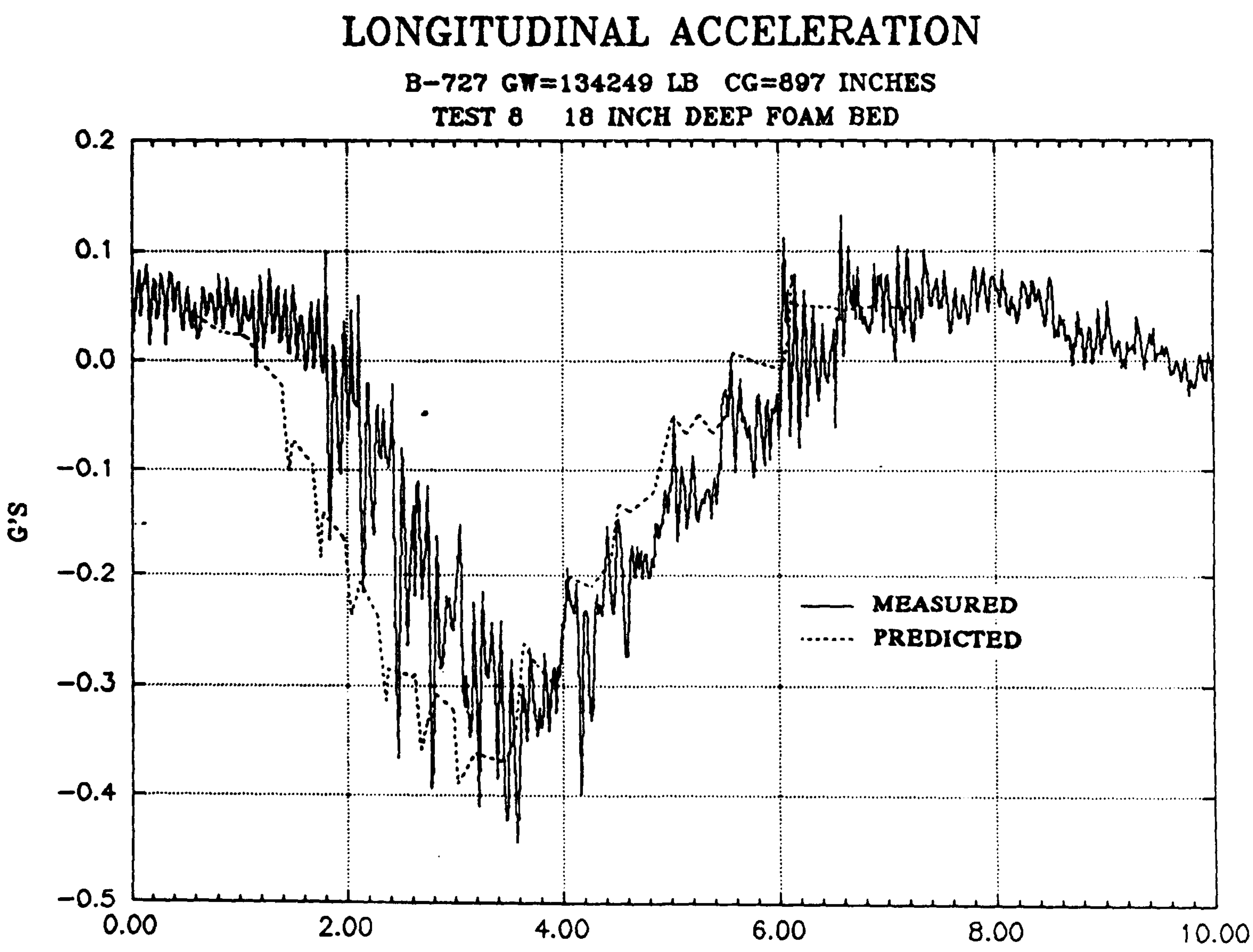

FIGURE 12. COMPARISON OF MEASURED AND SIMULATED LONGITUDINAL ACCELERATION

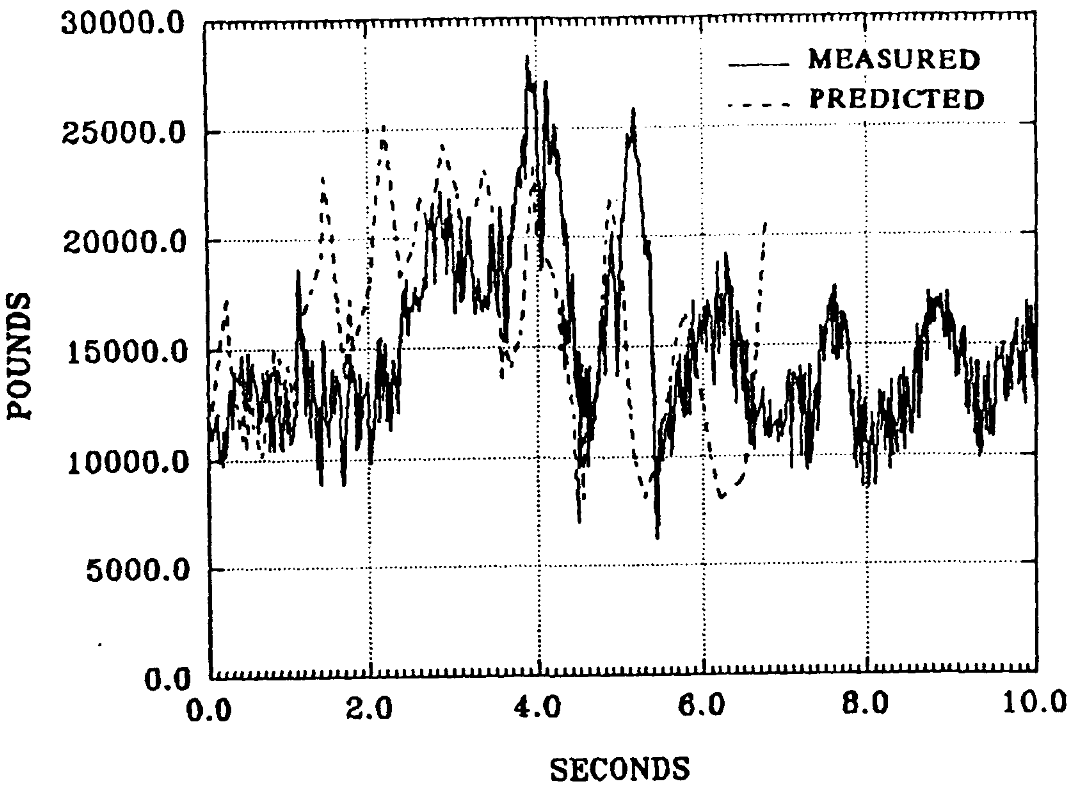

FIGURE 13. NOSE GEAR VERTICAL LOADS

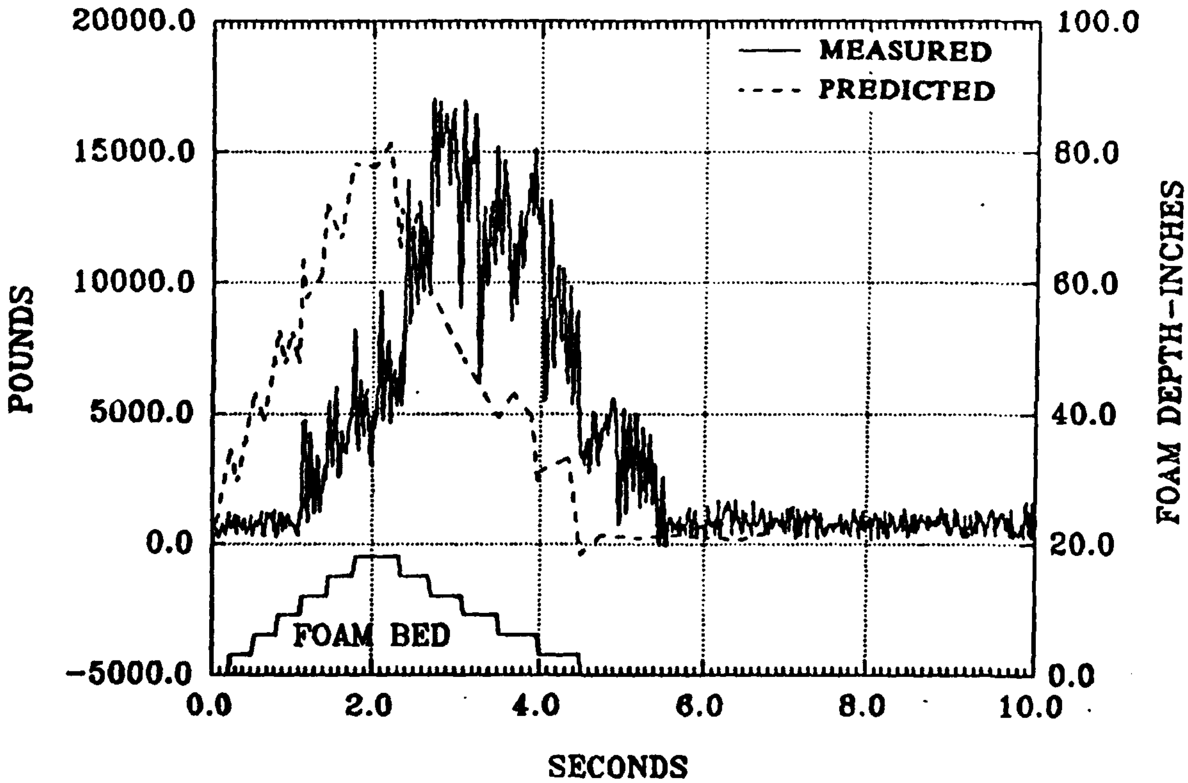

FIGURE 14. NOSE GEAR DRAG

curve is a result of landing gear fore and aft vibration which was not simulated in the computer model. This "noise" is <u>not important</u> in determining the overall aircraft drag on the landing gear because it is oscillatory, and the net effect on the aircraft drag is zero. This oscillatory "noise" <u>is important</u>, however, for determining the gear loads; and the computer program should be modified to account for these forces. In other words, the "noise" factor can be ignored when the model is to be used only to calculate arrestor bed effectiveness in stopping aircraft, but must be considered as a significant parameter in predicting possible damage to aircraft during research activities. The analytical model accurately predicted the drag force. Also note that the drag curve for the nose gear closely follows the shape of the foam bed depth. The deeper the foam, the greater the drag.

Figures 15 and 16 compare the <u>main</u> gear vertical forces and drag as measured during Test 8 and as predicted by the model. Figure 15 shows that the predicted vertical forces were quite accurate, as in the case of the nose gear. Figure 16, however, shows that the measured drag was about 10,000 pounds higher than predicted, and poses a dilemma as to which values are more correct. In this case there is evidence to support the validity of the analytical model prediction. First, the nose gear measured and predicted drag results were quite similar, lending credence to the predicted main gear drag values. Second, the measured acceleration/deceleration curve of figure 12 shows that the maximum deceleration was approximately 0.4 G's at a time of 3.6 seconds into the test. This deceleration would require a total drag on the aircraft of about 53,700 pounds. The nose gear drag at that time was about 13,000 pounds, so that the total drag on the main gear should be about 40,700 or 20,350 pounds on each gear.

Figure 16 shows that the measured drag load was approximately 32,000 pounds at the 3.6-second time spot, but that the predicted main gear drag was only about 22,000 pounds (remember to subtract 1 second for the simulated curve). This analysis shows that the measured main gear drag is too large by about 10,000 pounds and that the simulated drag is probably correct. As with the nose gear figure depiction, the foam bed longitudinal cross section is shown for reference. Again the magnitude of the drag on the main gear follows the depth of the foam bed closely.

Another measure of computer simulation accuracy relates to its ability to predict the ground speed profile of the aircraft while passing through the arrestor test bed. Figure 17 shows the comparison of measured and predicted ground speed for Test 8. The predicted speed reduction appears to be about 2 knots lower than the measured value, even though both started at the same speed. This must be considered a minor error, with the predicted ground speed values sufficiently accurate for designing the foam arrestor.

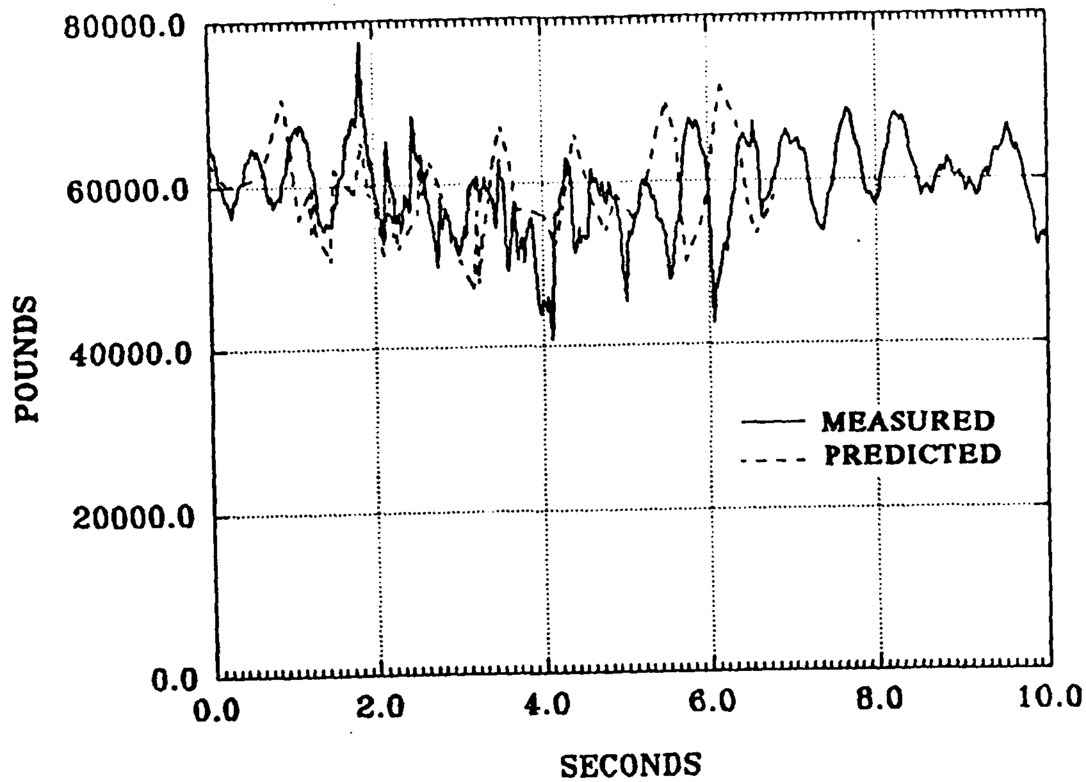

FIGURE 15. MAIN GEAR VERTICAL LOADS

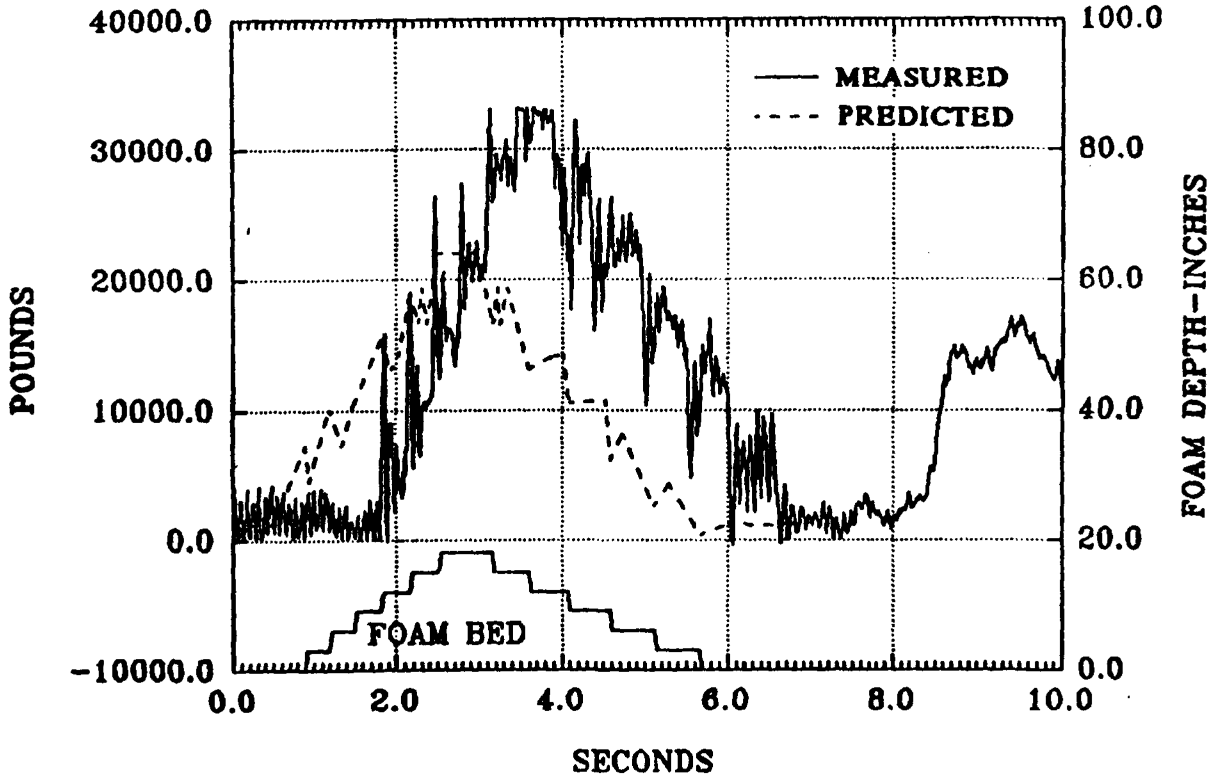

FIGURE 16. MAIN GEAR DRAG (ONE GEAR)

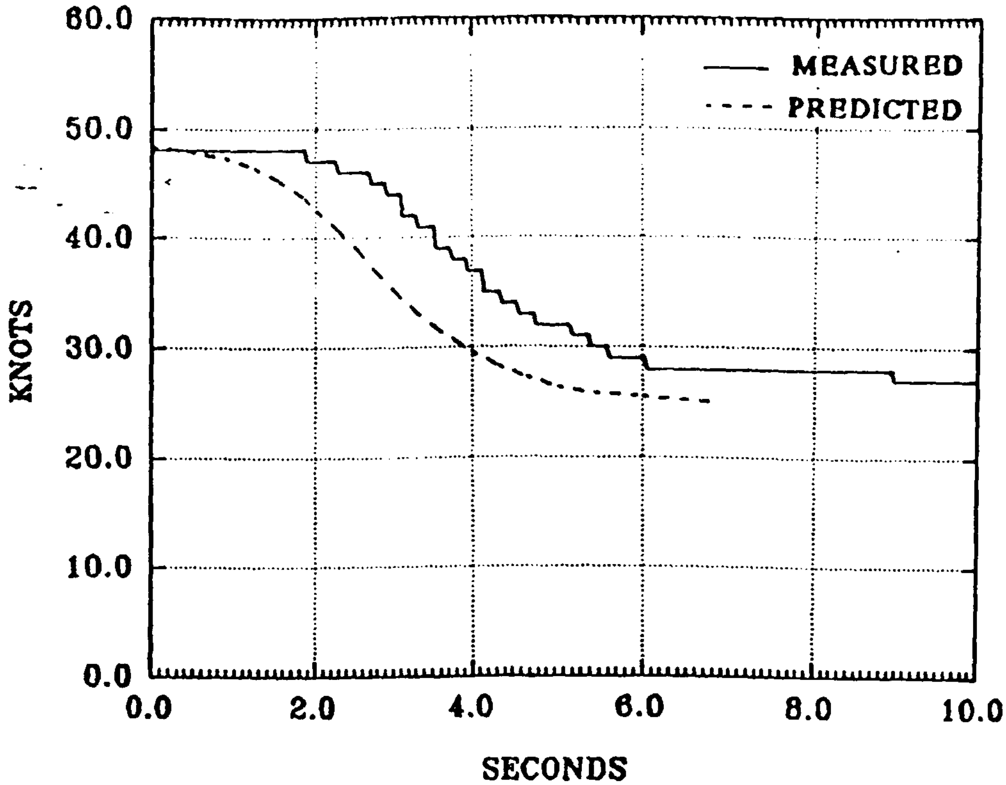

FIGURE 17. GROUND SPEED DURING TEST 8

3.3 EFFECTS OF AIRCRAFT BRAKING ACTION WITHIN THE FOAM BED.

Braking application is not an "automatic" function, except for the "anti-skid" feature found on most modern air-carrier aircraft. The decision to apply aircraft braking action rests with the pilot and his use, or non-use, during rollout after landing or aborted takeoff, cannot be predicted. Therefore, in evaluating the effectiveness of the foam arrestor bed some consideration must be given to the effect of aircraft braking action if applied.

The aircraft braking effectiveness within the arrestor bed must be as predictable as the braking performance of aircraft on airport runways under various conditions. Significant effort in past years has been expended in determining aircraft braking capabilities on runways having different surface conditions, i.e., wet, dry, snow covered, and ice covered. Using similar analysis techniques, we will now discuss some aspects of the contribution of brake application, if any, to the effectiveness of the foam bed in arresting aircraft.

When considering aircraft braking performance and conducting tests to determine its value, we must realize that retarding forces are produced not only by the friction resulting from braked-tire contact with the runway surface, but also by the effects of reverse thrust and aerodynamic drag. These latter forces, reverse thrust and aerodynamic drag, will normally be present, but they become increasingly less of a factor at speeds of 80 knots

or less. Slower speeds obviously produce less aerodynamic drag. Not so obvious is the erosion of engine thrust at lower speeds due to loss of ram effect. These factors must still be considered, however, in evaluating either braking or arrestor performance.

The principal braking forces, at the slower speeds, result from the available or applied coefficient of friction, μ, generated by the aircraft tires at the operating surface. The usual range of μ values encountered by the aircraft are 0.5 for a dry operating surface, 0.25 to 0.4 for a wet surface, and 0.02 to 0.1 for snow or icy surfaces. It is, of course, desirable to have the coefficient of friction as high as possible to obtain good braking performance.

The aircraft braking tire/surface forces are measured by determining the longitudinal deceleration at the aircraft Center of Gravity (CG) and/or by measuring the drag generated at the landing gear wheel tire/surface. During the tests under discussion, aerodynamic drag and engine thrust were minimized, as explained earlier, with the result that their effect upon deceleration measurements was of virtually no consequence.

The pilot of the aircraft has control of the braking forces generated at the tire/surface interface. Light brake pressure can generate a μ of 0.05 to 0.1, moderate brake pressure can generate a μ of 0.2 to 0.4, and high brake pressure can generate a μ of up to 0.5. Many aircraft overruns result from the fact that adverse tire/surface conditions, such as ice, can dramatically lower the μ. This tends to increase the stopping distance regardless of brake pressure applied. The purpose of the foam arrestor is to obtain the equivalent of a high coefficient of friction regardless of the tire/surface condition.

In figures 13, 14, 15 and 16, the measured and simulated landing gear vertical forces and drag were presented. The equivalent coefficient of friction, μ, attained by each component of the landing gear in the foam material can be determined by dividing the drag by the vertical force. This ratio is the DRAG RATIO. It is the same as that used to determine the coefficient of friction, μ, for a runway surface, except that the forces in the foam were determined at the gear axle rather than at the runway surface. The DRAG RATIO in the foam bed is shown for the aircraft nose and main gear on figures 18 and 19. These two figures show that at the deepest part of the foam bed, the DRAG RATIO was quite large for the nose gear and certainly equal to that attained with moderate braking of the main gear. With an even deeper foam bed dimension, it would appear that higher values for the DRAG RATIO could be attained.

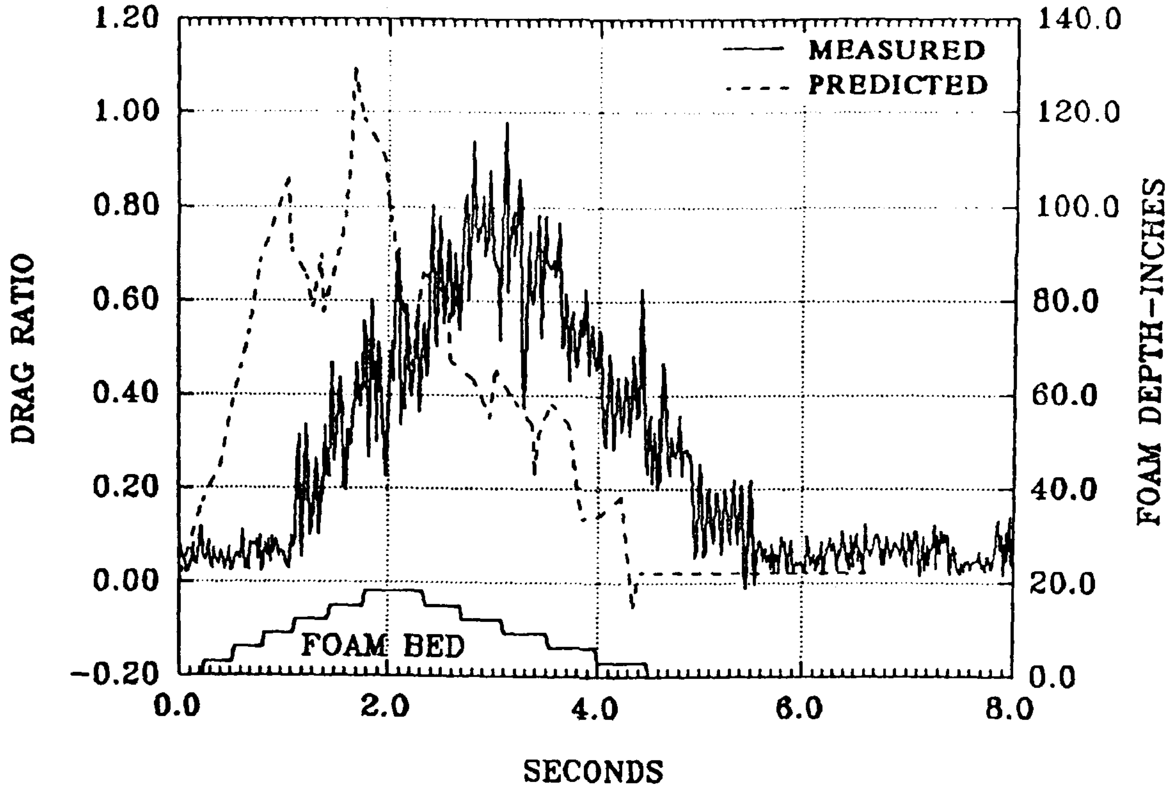

FIGURE 18. NOSE GEAR DRAG RATIO IN FOAM MATERIAL

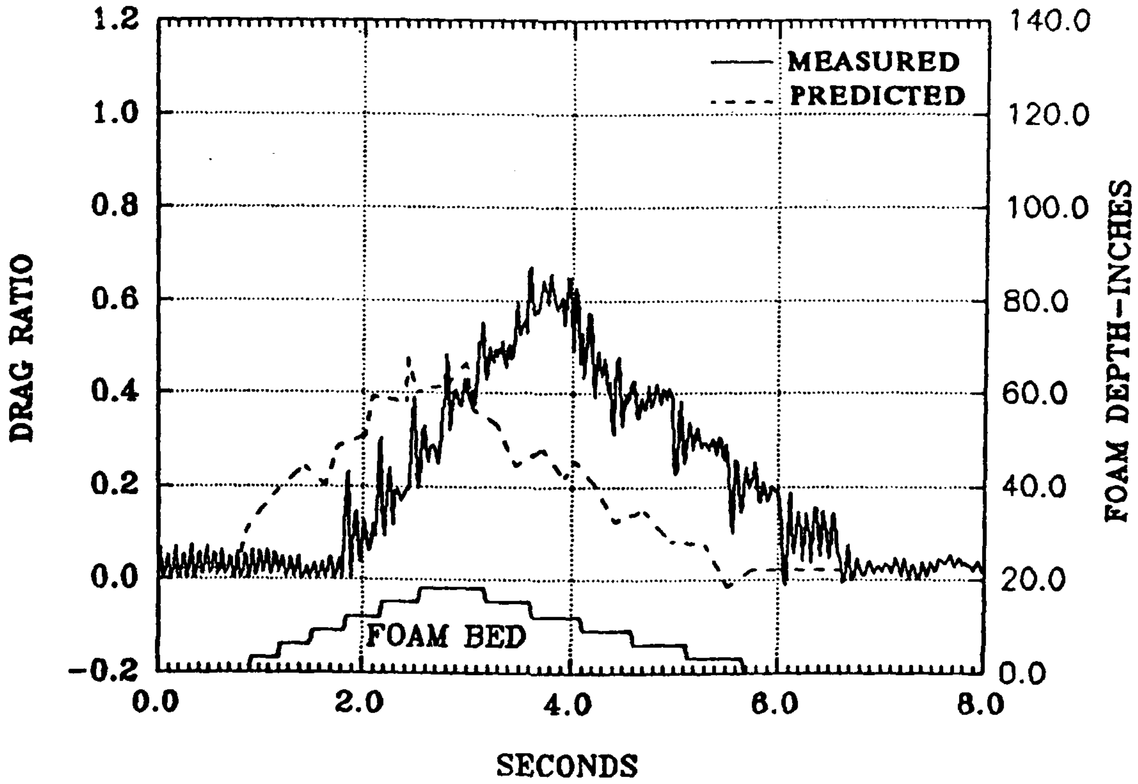

FIGURE 19. MAIN GEAR DRAG RATIO IN FOAM MATERIAL

The combined effect of the DRAG RATIO from both the nose and main gear is shown on figure 20. The DRAG RATIO for the measured and simulated curves was obtained by adding the nose and main gear drag at each time increment, and then dividing that sum by the weight of the aircraft. This is not quite the same DRAG RATIO as described above but it differs only by the difference in the inertial weight and static weight of the aircraft at the CG. By way of explanation, figure 21 shows the vertical acceleration of the aircraft CG, which can be seen to oscillate to average values of ± 0.1 G about the mean. This can be attributed to a difference of approximately 13,000 pounds between the aforementioned inertial and static aircraft weights. This difference, compared to the total test aircraft weight of 135,000 pounds, is relatively insignificant and should not affect the determination of total aircraft DRAG RATIO. The much higher values of acceleration are due to local structural deformations and would not contribute to the DRAG RATIO. Also shown on figure 20 is the measured deceleration curve obtained during Test 8. The deceleration curve and the simulated DRAG RATIO show remarkable similarity. This similarity indicates that the deceleration is a good indicator of the DRAG RATIO for the aircraft in a foam bed.

3.4 TEST RESULTS WITH BRAKES APPLIED.

During the above described testing, brake pressure was not applied by the pilot while in the foam bed. It is believed that in most cases of potential aircraft runway overrun, the pilot or copilot will instinctively apply brakes throughout the rollout maneuver, to include transit through the arrestor bed. Since the foam has very little shear strength, it was decided to conduct a test (Test 4) to determine the effect of simultaneous braking on the foam arrestor performance.

Figure 22 shows a plot of the main gear vertical load and drag time history resulting from main gear brake application prior to and while passing through the 6-inch deep, Type 1, foam test bed. The nose gear drag load is also depicted for reference. The main gear drag increased, initially and prior to test bed entry, to a "moderate" braking level. As the main gear wheels entered the foam bed, there was a marked reduction in measured drag, with the lower level values being sustained throughout the time that the main gear wheels were transiting the arrestor bed. During the period of gear transit through the test bed, the drag did not go to zero, but rather sustained a value close to that measured during preliminary testing, with no brake application, on this same test bed configuration. These results indicate that braked wheels have little or no effect upon the drag induced by the foam bed. Similar results were obtained during the British (reference 1) test program.

3.5 FIRE/RESCUE EQUIPMENT ACCESSIBILITY.

Subsequent to completion of Test 8, arrestment with the deepest test bed configuration, the P-19 fire truck was driven through, and maneuvered in, the debris of the foam bed. No difficulties were encountered in executing turning and backing maneuvers with the vehicle, nor were individuals on foot unduly hampered while moving within the rutted test bed. Difficulty in performing rescue operations within a foam test bed can be expected to be about equivalent to that encountered at any other emergency rescue site.

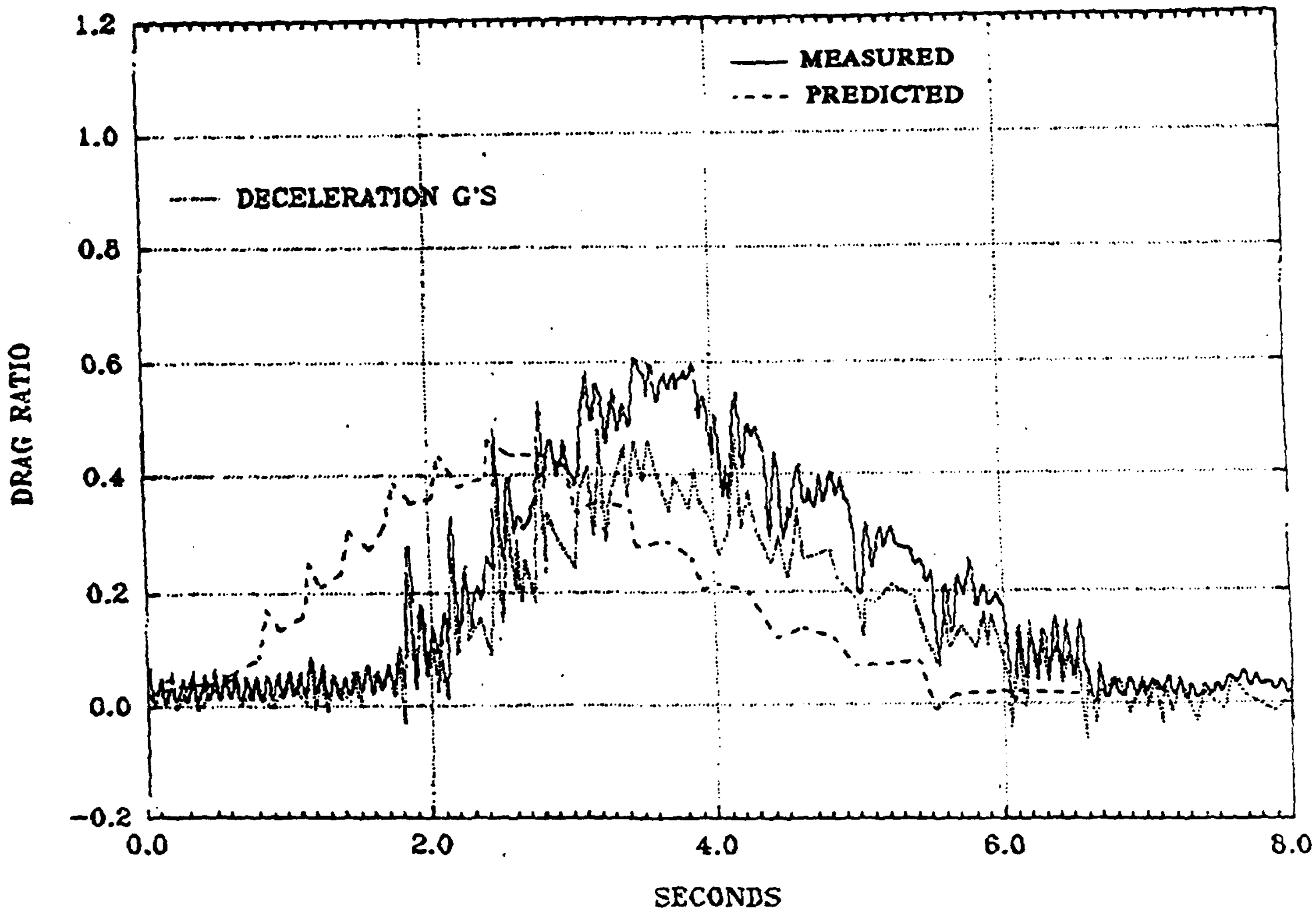

FIGURE 20. AIRCRAFT TOTAL DRAG RATIO IN FOAM MATERIAL - TEST 8

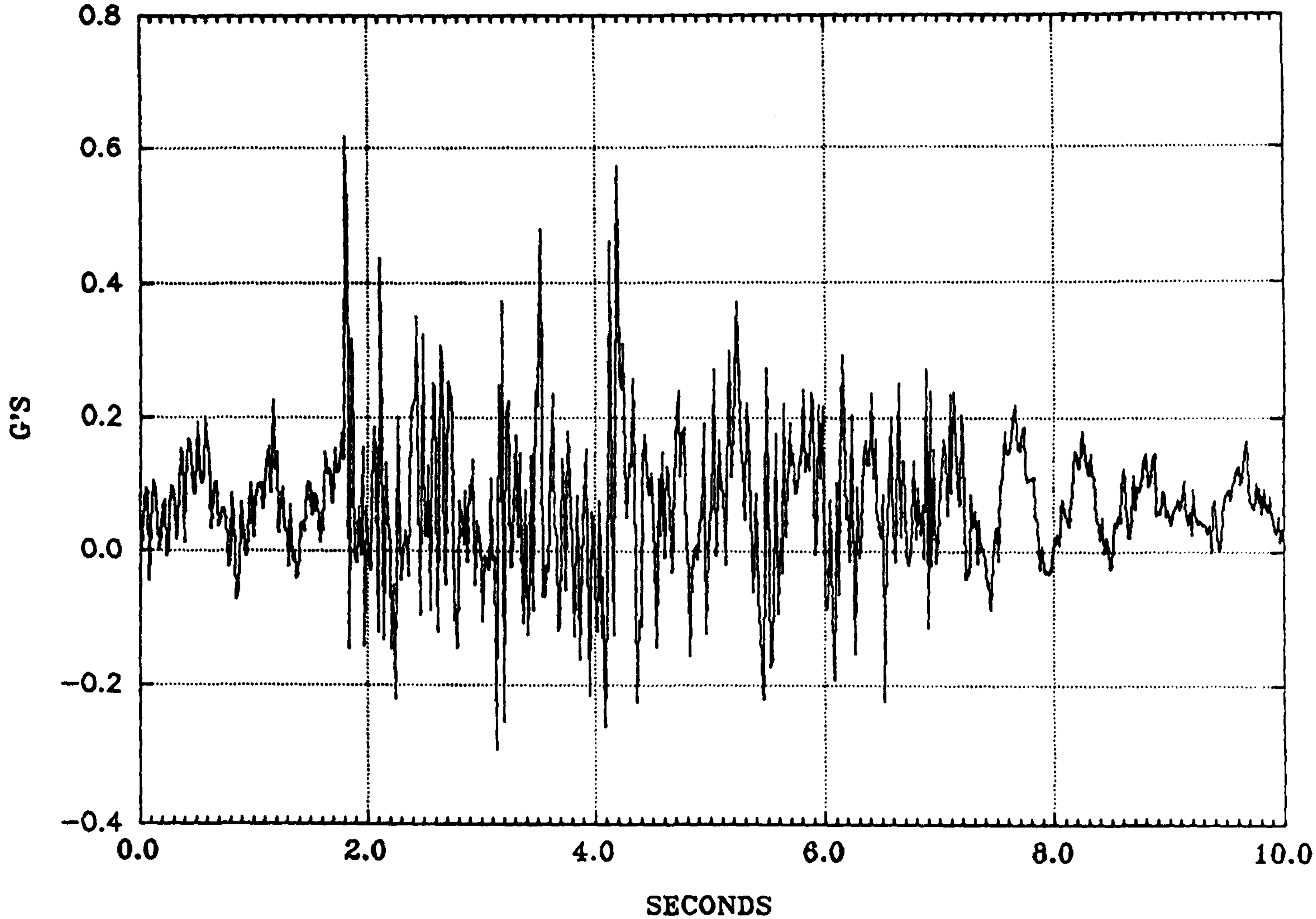

FIGURE 21. MEASURED CENTER OF GRAVITY NORMAL ACCELERATION TEST 8

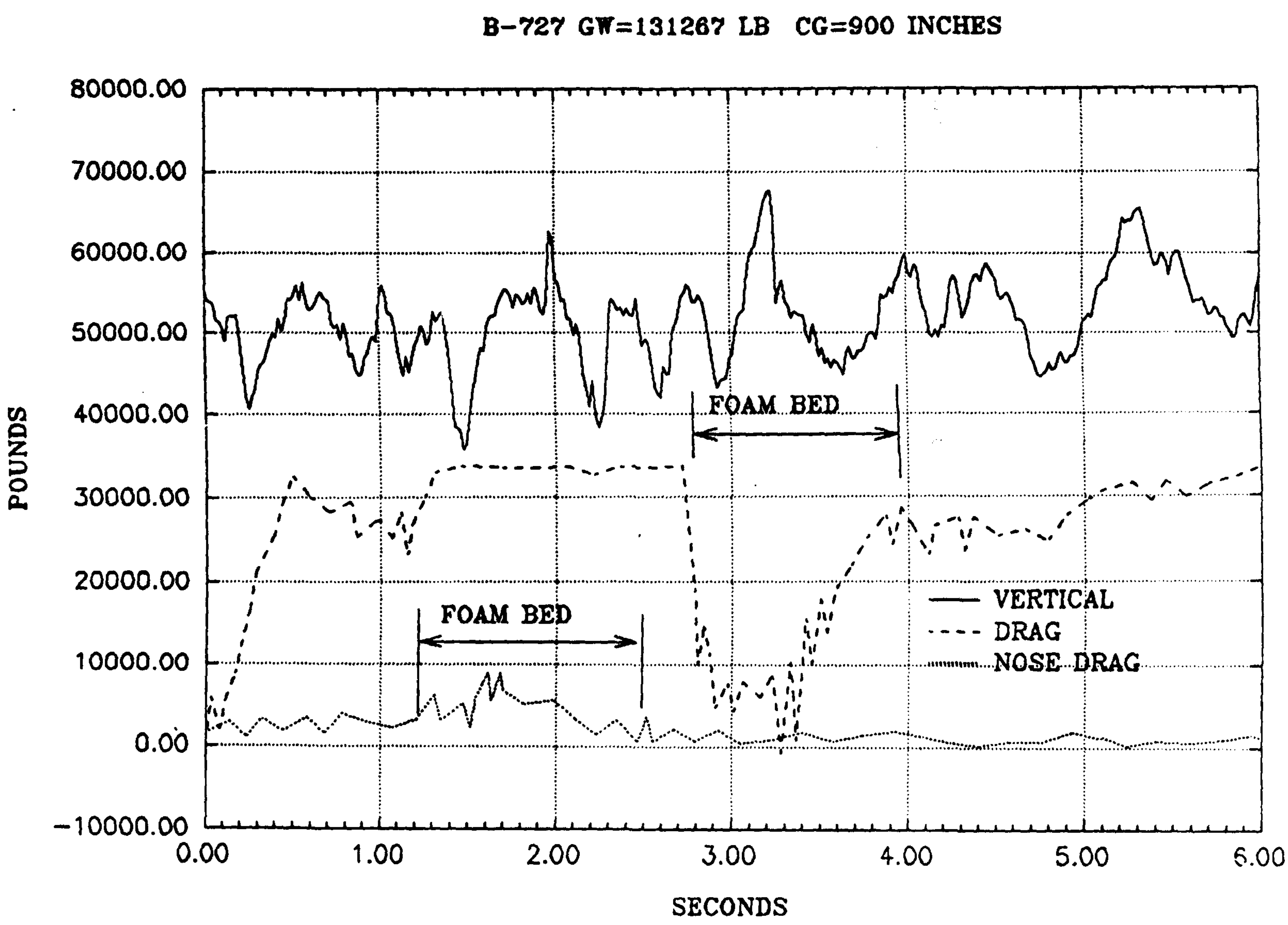

FIGURE 22. RIGHT MAIN GEAR BRAKING ON TYPE 1 FOAM TEST BED

4. CONCLUSIONS.

From the results of this soft-ground arresting system testing effort, we can conclude that:

- Accuracy of the analytical model in predicting Boeing 727 aircraft landing gear loads, longitudinal Center of Gravity acceleration, and deceleration in the foam arrestor was successfully validated. All measured parameter values were found to be within 10 percent of those predicted by the model, with the majority having even closer correlation.

- The 18-inch-deep phenolic foam bed was effective in decelerating the large commercial aircraft as predicted by the analytical model. It provided a DRAG RATIO (coefficient of friction) of 0.4, which is considered to be equivalent to "good" aircraft braking action.

- Fire/Rescue equipment and personnel can maneuver and conduct emergency operations within the debris of a foam arrestor bed without difficulty.

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